



1016

DEVONIAN SHALE PLAYS IN THE BLACK WARRIOR BASIN AND APPALACHIAN THRUST BELT OF ALABAMA

Jack C. Pashin, Rashmi L. B. Grace, and David C. Kopaska-Merkel
Geological Survey of Alabama
P. O. Box 869999, Tuscaloosa, AL 35486

ABSTRACT

The Black Warrior basin and Appalachian thrust belt of Alabama are frontier areas for shale gas production, and diverse opportunities for development exist in Devonian strata. The Chattanooga Shale is being developed along the southeast margin of the Black Warrior basin and along the frontal structures of the Appalachian thrust belt. A thick, unnamed Silurian-Devonian section is prospective in the interior of the thrust belt. Integrated geological analysis indicates that the characteristics of the shale differ markedly depending on the geologic setting, and that these characteristics should be taken into account during exploration and development.

INTRODUCTION

Exploration and development of shale gas resources is in an early stage in Alabama, where activity is focused on diverse opportunities in Cambrian through Mississippian strata (Pashin, 2008). Devonian shale formations present a range of opportunities for unconventional gas development in Alabama, and these opportunities differ markedly depending on the geologic setting. The main areas of interest to date are in the Black Warrior basin and the Appalachian thrust belt (fig. 1). In northeastern Alabama, production has been established in the Chattanooga Shale along the frontal structures of the Appalachian thrust belt. Farther southwest, in west-central Alabama, exploration is active along the southeastern margin of the Black Warrior basin. South of this area, prospects are being evaluated in the interior of the Appalachian thrust belt, where a thick, unnamed succession of organic-rich shale appears to span the Silurian-Devonian section (Pashin et al., 2010).

This paper summarizes the geology of Devonian shale in Alabama and is designed to help guide the exploration and development of shale gas resources in diverse geologic settings. This work is part of a three-year program sponsored by the Research Partnership to Secure Energy for America (RPSEA). The objective of this program is to develop and promote geologic methods for the evaluation of shale gas resources. Accordingly, this contribution takes a systematic approach to the characterization of Devonian shale in Alabama.

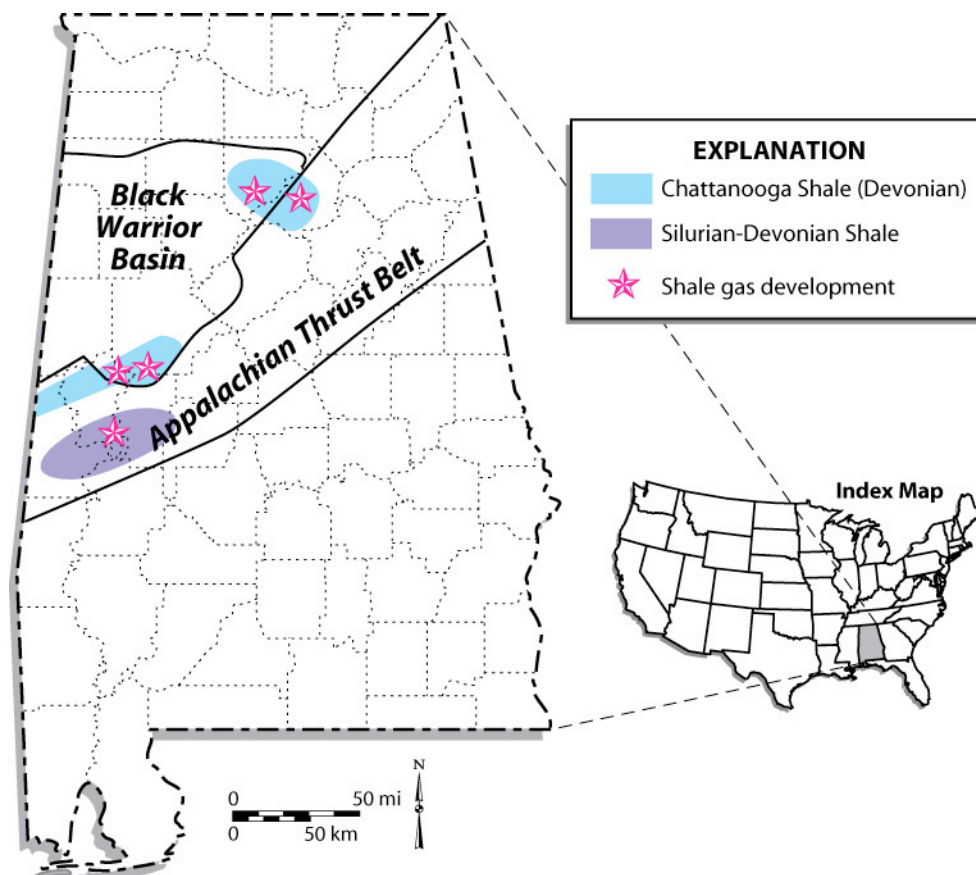


Figure 1.—Location map showing focus areas for Devonian shale development in the Black Warrior basin and Appalachian thrust belt of Alabama.

The fundamental properties of shale gas reservoirs are established partly in the original depositional environment, and so the paper begins with a summary of stratigraphy and sedimentation. Deformation affects the depth, geometry, continuity, and fracture architecture of shale formations, thus the paper continues with a discussion of geologic structure. The discussion then shifts to basin hydrodynamics and geothermics, which can influence the storage and mobility of natural gas in unconventional reservoirs. Similarly, petrologic and geochemical variables can affect reservoir quality, and hence, the storage and producibility of natural gas. The paper finishes with a discussion that synthesizes the results of this investigation into conceptual geologic models that can help facilitate exploration and development.

STRATIGRAPHY AND SEDIMENTATION

Devonian strata in Alabama include a variety of carbonate and siliciclastic rock types, including an organic-rich shale facies that is characteristically, black, fissile, and brittle (fig. 2). Although the shale can at first glance appear lithologically homogeneous, parts of the shale are argillaceous, whereas other parts are siliceous or calcareous. These strata disconformably overlie strata of Silurian age, and the characteristics of the Devonian section vary considerably depending on location. In the Appalachian thrust belt, sandstone and limestone assigned to the Frog Mountain Sandstone form the lower part of the Devonian section and are largely of Early to Middle Devonian age. Equivalent strata in the Black Warrior basin are dominated by a northeast-thinning wedge of limestone and chert and have not been assigned to any formal stratigraphic unit (Kidd, 1975; Thomas, 1988) (figs. 3, 4).



Figure 2.—Outcrop of the Chattanooga Shale in the Appalachian thrust belt of Alabama showing sheared and folded zone in lower part and well-developed orthogonal joint system in upper part.

This carbonate-dominated section is overlain disconformably by the organic-rich black shale of the Chattanooga Shale (figs. 2-4), which is of Middle to Late Devonian age. The shale onlaps the disconformity and directly overlies Silurian strata northeast of the pinchout of the Devonian limestone-chert section (Conant and Swanson, 1961; Kidd, 1975; Rheams and Neathery, 1984). The Chattanooga is overlain sharply by the Lower Mississippian Maury Shale, which is commonly thinner than 2 feet, and the Maury is in turn overlain by the Fort Payne Chert.

The Chattanooga Shale is characterized by elevated radioactivity and is thus readily identified in gamma ray logs (figs. 3, 4). An isopach map of the Chattanooga Shale in the Black Warrior basin

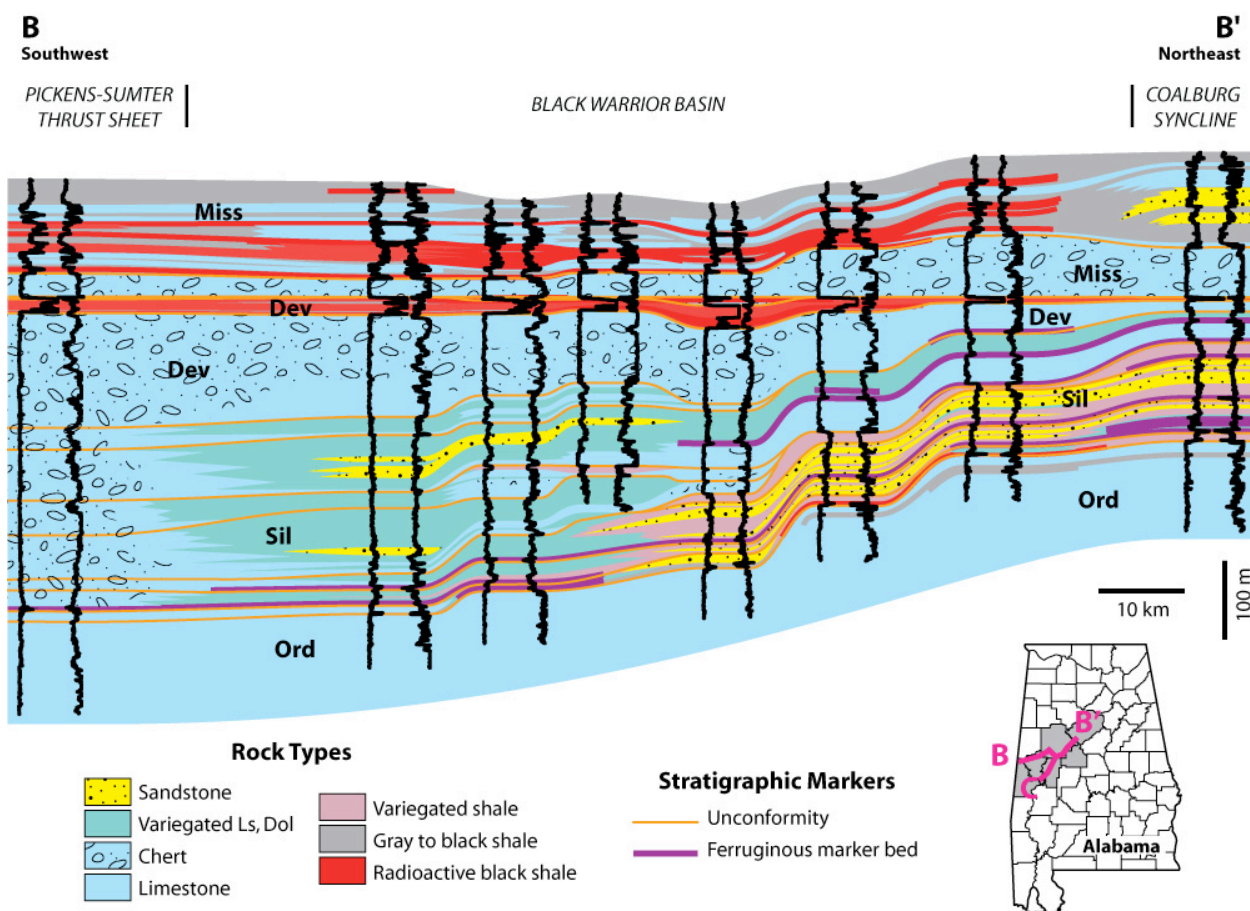


Figure 3.—Regional stratigraphic cross section showing the correlation of Ordovician through Mississippian strata in the Black Warrior basin and the Appalachian thrust belt (modified from Pashin et al., 2010).

demonstrates that shale thickness varies regionally (fig. 5). The shale is thinner than 10 feet and is locally absent in much of Lamar, Fayette, and Pickens Counties, which is the principal area of conventional oil and gas production in the Black Warrior Basin. The shale is thicker than 30 feet in a belt that extends northwestward from Blount County into Franklin and Colbert Counties. GeoMet, Incorporated, is producing shale gas from vertical and directional wells near the southeast end of the belt in Blount and Cullman Counties. A prominent depocenter is developed along the southwestern basin margin in Tuscaloosa and Greene Counties. Here, the shale is consistently thicker than 30 feet and is locally thicker than 90 feet. Energen Resources Corporation and Chesapeake Energy Corporation have been exploring this depocenter, and activities have included the drilling and testing of horizontal wells.

An exceptionally thick section of organic-rich shale is preserved deep in the interior of the Appalachian thrust belt below the Gulf Coastal Plain in Greene and Hale Counties. Accordingly, the structure containing these strata is called the Greene-Hale synclinorium (Pashin et al., 2010). Three wells penetrating the Silurian-Devonian section logged more than 1,750 feet of section dominated by organic-rich shale with numerous radioactive zones (fig. 4). The Silurian-Devonian boundary is placed provisionally at the base of a zone with low radioactivity and elevated resistivity that appears to correlate with the Devonian carbonate-chert section in the Black Warrior basin. Core from this resistive zone in the Burke 29-7 #1 well in Hale County contains principally dark gray micrite and shale with horizontal laminae and soft-sediment deformation structures and thus contrasts sharply with the chert-bearing carbonates of

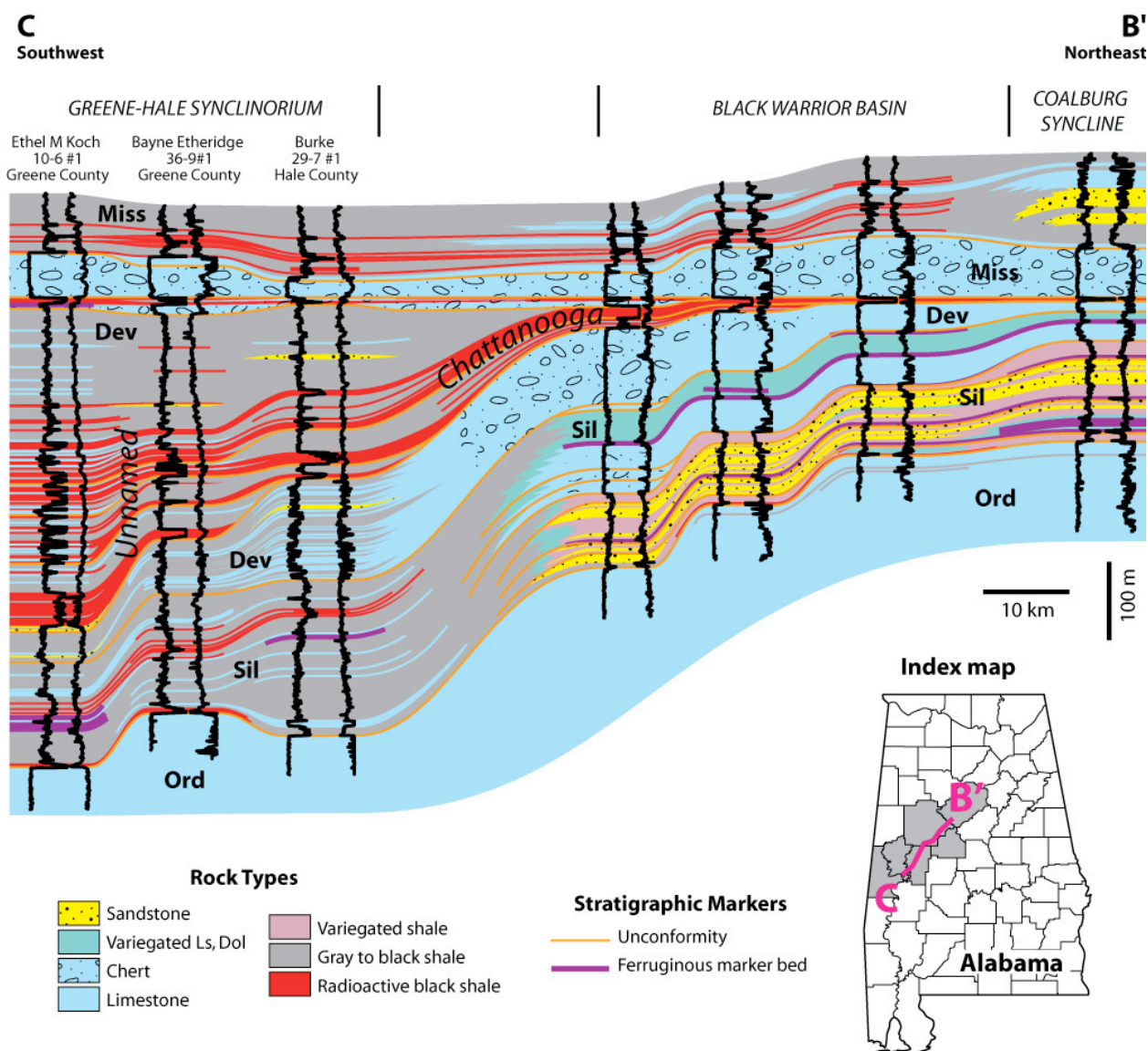


Figure 4.—Regional stratigraphic cross section showing the correlation of Ordovician through Mississippian strata in the Black Warrior basin and the Greene-Hale synclinorium (modified from Pashin et al., 2010).

the Black Warrior basin. Core of the Devonian section includes black shale interstratified with gray shale, siltstone, and crinoidal limestone (Bayne-Etheridge 36-9 #1 well).

Black, fissile shale is the signature rock type of the Devonian shale section in the Appalachian region, and close examination reveals a variety of physical and biogenic sedimentary structures (fig. 6). Much of the shale is horizontally laminated (fig. 6A), and low-amplitude ripple cross-strata can be discerned in places. In some cores, thin beds of structureless mudstone occur within thinly laminated shale (fig. 6B). Much of the black shale is bioturbated (fig. 6C), and examination of bedding planes reveals that much of the laminated shale contains horizontal burrows (fig. 6D). Body fossils are not common in the shale, although some siliceous layers are rich in radiolarians (fig. 7) or monaxon-type spicules. Soft-sediment deformation is common in the Devonian shale of Alabama, particularly in the Greene-Hale synclinorium (Bayne-Etheridge 36-9 #1 well). Small-scale overturned and recumbent folds have been observed in the

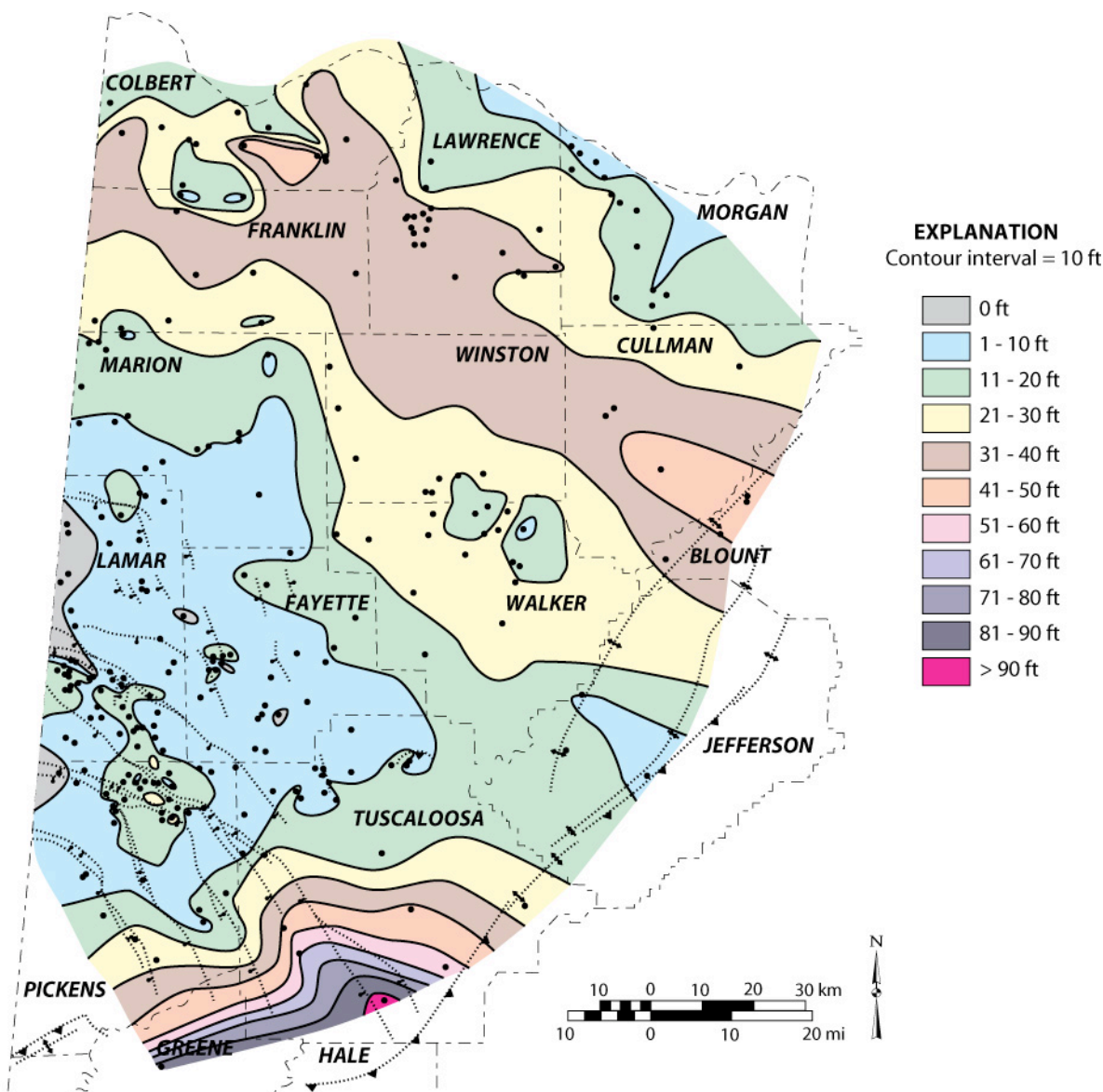


Figure 5.—Isopach map of the Chattanooga Shale in the Black Warrior basin of Alabama (modified from Pashin, 2008).

gray shale, siltstone, and limestone that separates the black shale units. Within the black shale, a tilted block that is overlapped by younger strata was also observed (fig. 6E).

The depositional environment of Devonian black shale has long been a subject of debate. Conant and Swanson (1961) favored a shallow-water origin in which organic-rich mud accumulated in what could be considered as a cratonic lagoon. More recent workers recognized that the black shale facies is linked to the Acadian foreland basin in the central Appalachians and developed euxinic basin models in which the shale accumulated below storm wave base in water depths ranging from less than 100 to more 700 feet (e.g., Ettensohn, 1985; Ettensohn et al., 1988). Indeed, depositional processes in the black shale basin were highly complex, and evidence for in-situ marine faunas and high-energy structures indicates that some of the shale accumulated in dysoxic environments and was episodically subjected to reworking above storm wave base in the cratonic reaches of the basin (e.g., Pashin and Ettensohn, 1992, 1995;

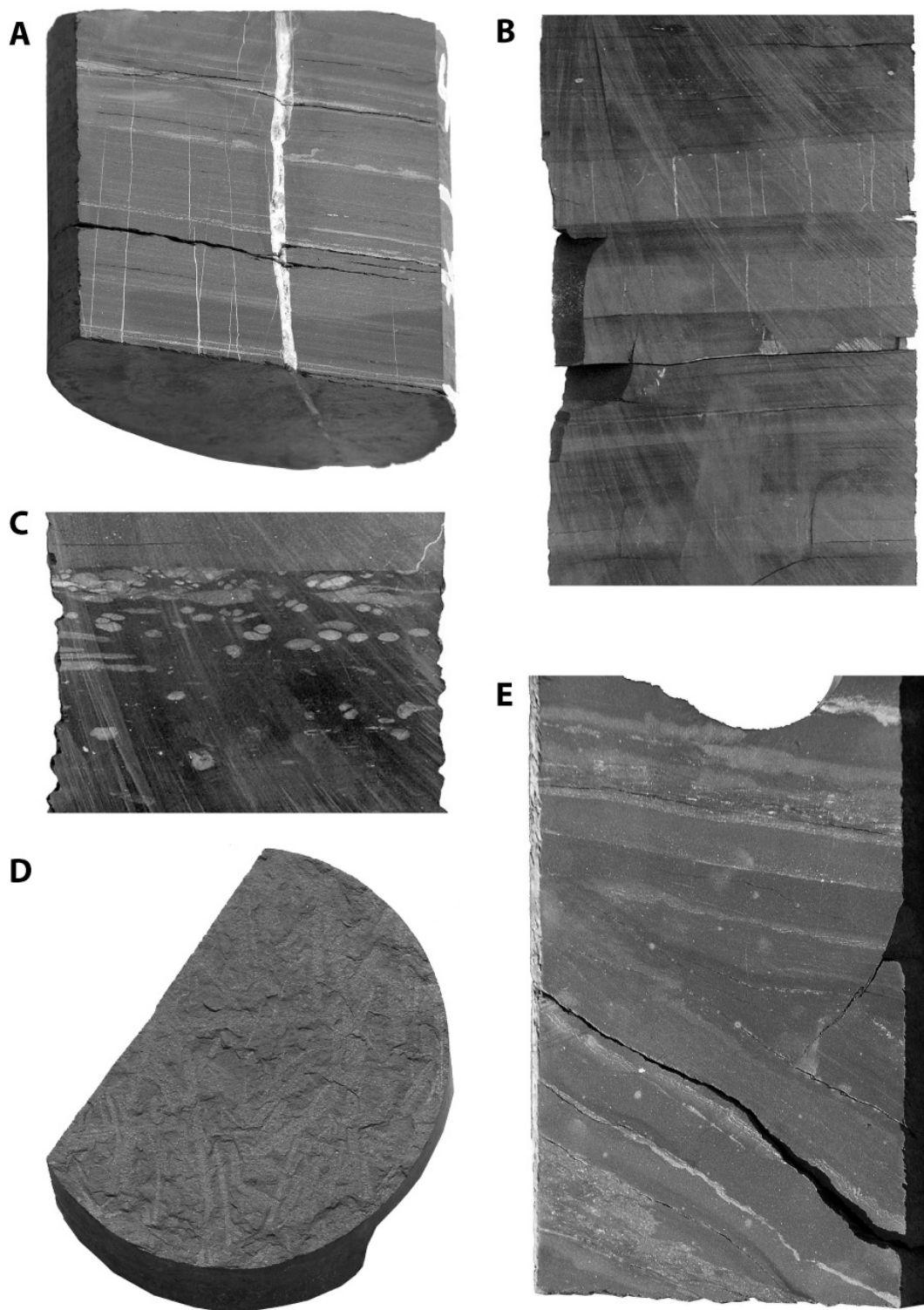


Figure 6.—Core photographs showing physical and biogenic sedimentary structures in Devonian black shale. A) Laminated shale and siltstone with calcite veins, Bayne Etheridge 36-9 #1 well, 8,444 ft. B) Laminated shale containing thin beds of structureless mudstone, Lamb 1-3 #1 well, 9,168 ft. C) Shale with siltstone-filled burrows, Lamb 1-3 #1 well, 9,174 ft. D) Bedding plane with horizontal burrow fills Bayne Etheridge 36-9 #1 well, 8,441 ft. E. Steeply dipping strata onlapped by near-horizontal strata, Bayne Etheridge 36-9 #1 well, 8,446 ft.

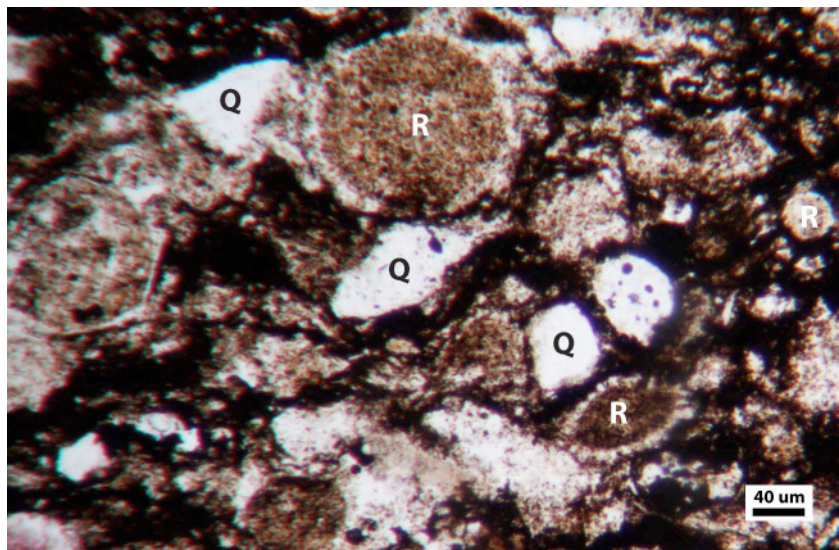


Figure 7.—Photomicrograph showing radiolarians (R) and detrital quartz (Q) in the Chattanooga Shale (Weyerhaeuser 2-43-2402 well, 8,204 ft, Greene County, Alabama).

Schieber, 1994). Layers rich in radiolarians (fig. 7), moreover, suggest that upwelling of nutrient-laden water supported plankton blooms in the Chattanooga basin.

Evidence from cores in the Black Warrior basin and the Greene-Hale synclinorium (fig. 6) indicates that black shale sedimentation in Alabama was dynamic. Bioturbation indicates that bottom water was at times oxygenated enough to support some infauna, and ripple cross-strata demonstrate that some sedimentation was associated with currents. The structureless shale layers within the laminated shale may represent distal mudflows. Regional facies relationships and soft-sediment deformation further suggest that Devonian shale sedimentation in the Greene-Hale synclinorium occurred on a slope. The transition from chert-bearing ramp carbonates to laminated, organic-rich shale and micrite is suggestive of a carbonate bank margin. Small-scale recumbent and overturned folds, moreover, are characteristic of submarine slumps and slides with significant lateral transport (Farrell and Eaton, 1987), and the tilted shale that is overlapped by younger sediment may be part of a slump structure (fig. 6E).

At a regional scale, Devonian tectonics and sedimentation in Alabama appear more complex than previously realized. The thin, widespread Chattanooga Shale of the Black Warrior basin and Appalachian thrust belt appears to have been deposited in a cratonic shelf setting that was, for the most part, tectonically stable. Thickening of the shale in the depocenter of southern Tuscaloosa, northern Greene, and northern Hale Counties (fig. 5) corresponds with a younger depocenter that persisted during Early Pennsylvanian time and has been interpreted as the product of Appalachian thrust and sediment loading (Pashin, 1994; 2004). Thus, the Devonian depocenter appears to foreshadow later foreland basin deformation. Indeed, the thick Devonian section in the Greene-Hale synclinorium may be a remnant of an Acadian foreland basin.

GEOLOGIC STRUCTURE

Devonian shale in the Black Warrior basin and Appalachian thrust belt contains a diverse array of extensional and compressional geologic structures. The Black Warrior basin is a late Paleozoic foreland basin that formed adjacent to the juncture of the Appalachian and Ouachita orogenic belts (Thomas, 1977, 1988). The basin can be characterized structurally as a southwest-dipping homocline that is broken by numerous normal faults (fig. 8). The faults strike west to northwest, and trace length ranges from less

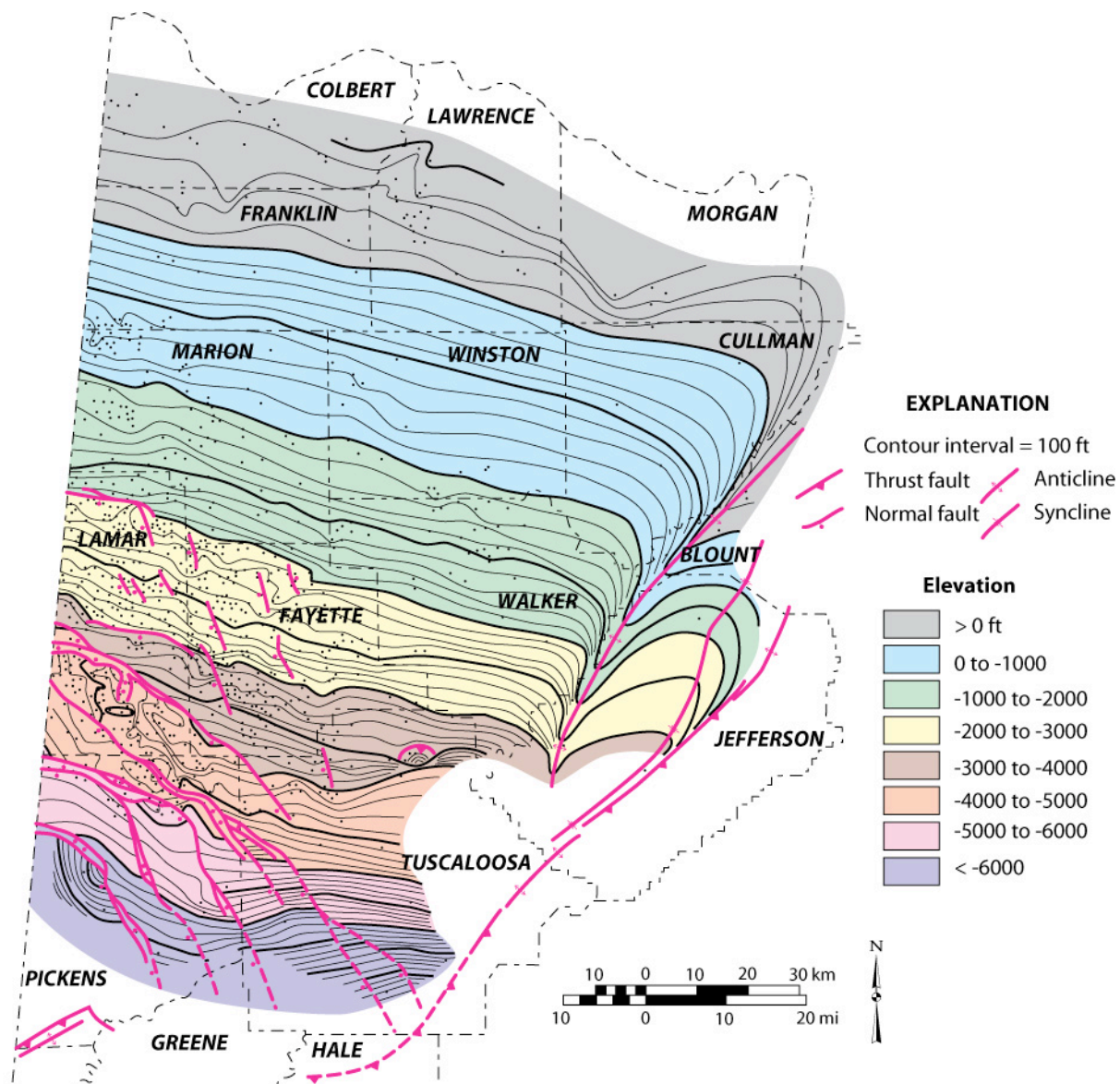


Figure 8.—Structural contour map of the top of the Tuscumbia Limestone in the Black Warrior basin of Alabama (modified from Pashin and Rindsberg, 1993).

than one mile to tens of miles. Displacement of faults that can be imaged seismically is generally greater than 50 feet and is in places greater than 1,000 feet (e.g., Groshong et al., 2009, 2010).

Appalachian folds and thrust faults strike northeast and are superimposed along the southeast margin of the homocline. The basin is developed on the Alabama Promontory, which is a protuberance of the Laurentian continental platform that formed during late Precambrian-Cambrian Iapetan rifting. Ouachita orogenesis was initiated along the southwest margin of the promontory during Mississippian time (Thomas, 1977). The Black Warrior can be considered to be mainly an Ouachita foreland basin. However, the Chattanooga depocenter and the Greene-Hale synclinorium may record Acadian tectonism along the Appalachian side of the promontory, where major Appalachian thrust and sediment loads were later active during Pennsylvanian time (Pashin, 2004).

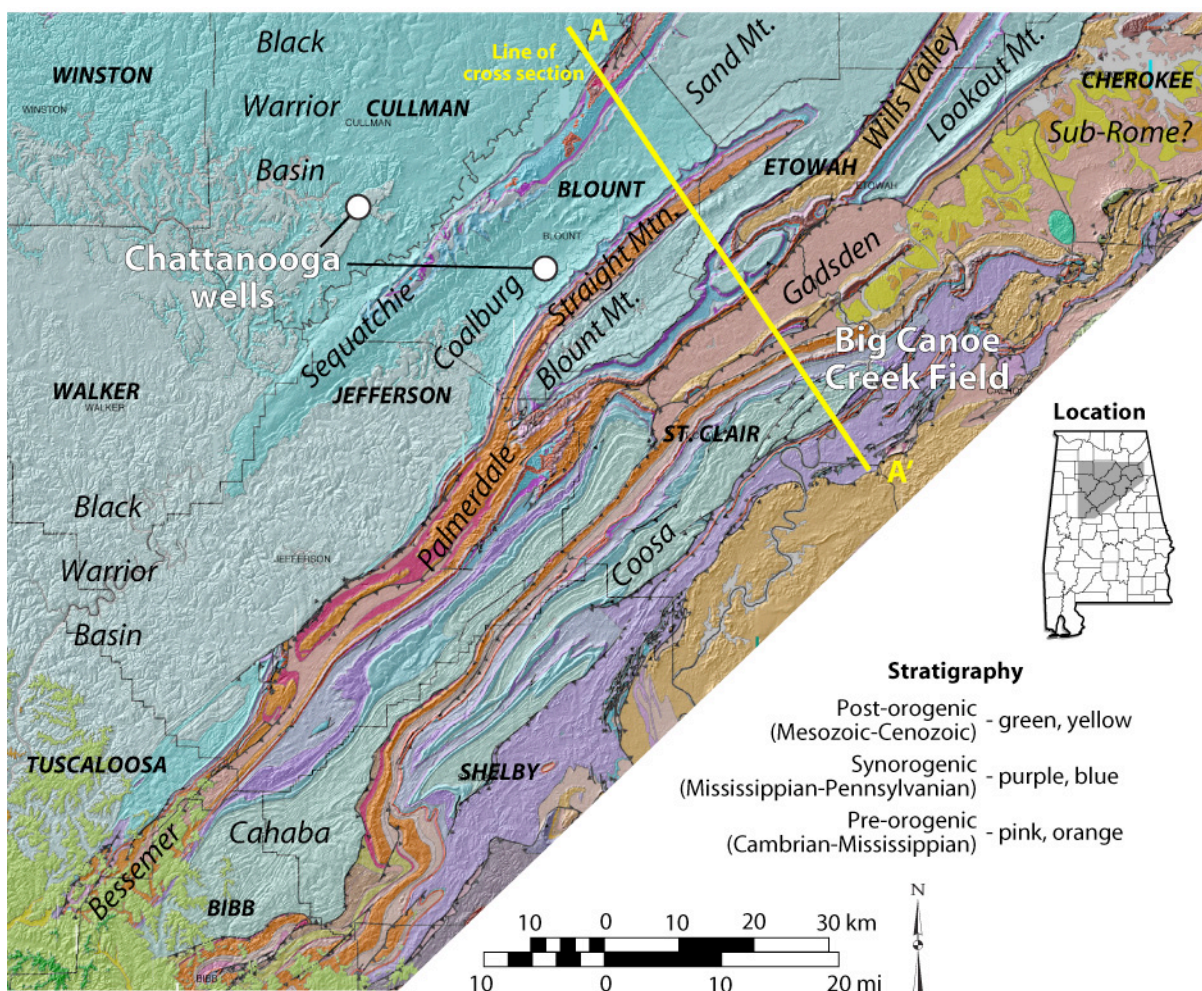


Figure 9.—Geologic map showing major structures of the Appalachian thrust belt and relationship to Chattanooga Shale gas production in Blount and Cullman Counties, Alabama (modified from Pashin, 2008).

The Appalachian thrust belt separates the gently dipping strata of the Black Warrior Basin from the crystalline core of the Appalachian orogen. The thrust belt is composed of deformed pre-orogenic carbonates of Cambrian through Mississippian age and synorogenic siliciclastic rocks of Upper Mississippian and Lower Pennsylvanian age (e.g., Thomas, 1985; Thomas and Bayona, 2005) (figs. 9, 10). The frontal part of the thrust belt, where shale gas exploration has been concentrated, is dominated by thin-skinned deformation in which Paleozoic strata have been translated cratonward above a basal detachment in Cambrian shale (Rodgers, 1950; Thomas, 1985, 2001).

The Cambrian shale hosts structures that range from frontal and lateral thrust ramps to giant antiformal stacks of intensely deformed shale (fig. 10). Above the Cambrian shale is a stiff carbonate succession of Cambrian-Ordovician age. This carbonate succession is the strongest stratigraphic unit in the thrust belt, and deformation is manifested mainly as frontal and lateral ramps that commonly extend upward into younger strata. Silurian through Pennsylvanian strata constitute a large volume of interbedded shale, sandstone, and limestone that is substantially weaker than the Cambrian-Ordovician carbonate. Regardless, frontal ramps commonly rise upward through the complete Cambrian-Pennsylvanian section. Thus in many areas, the stratigraphic section above the basal detachment was transported cratonward as a single lithotectonic unit. The Cambrian-Ordovician section crops out in a series of ramp anticlines and major fold limbs, whereas the Mississippian-Pennsylvanian section is

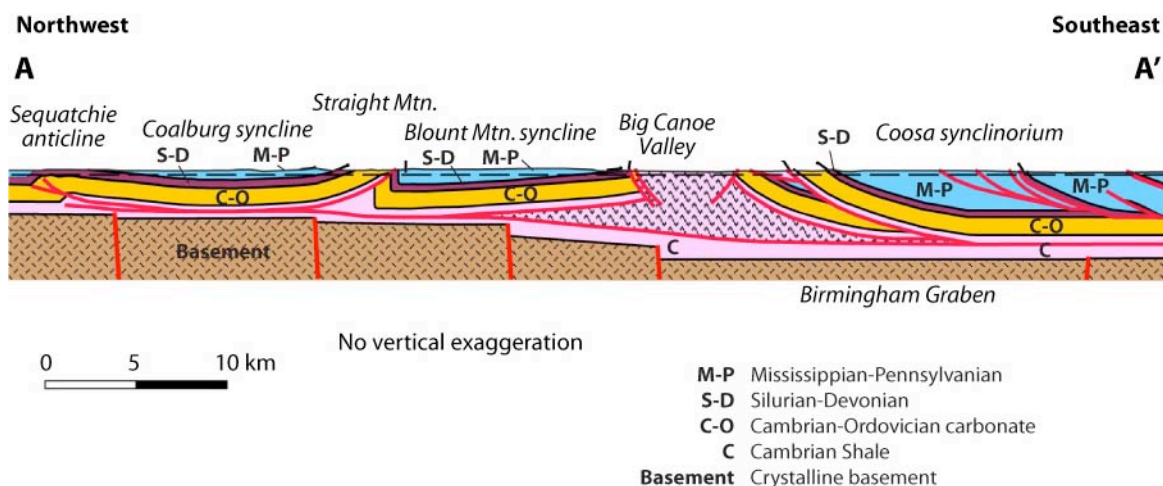


Figure 10.—Structural cross section of the Appalachian thrust belt in Alabama (modified from Thomas and Bayona, 2005). See Figure 9 for location.

preserved in broad, flat-bottomed synclines. Locally, however, upper-level thrust flats and secondary detachments are developed at the top of the Cambrian-Ordovician carbonate section and within weak shale units in the Ordovician-Pennsylvanian section (e.g., Thomas, 1985; Pashin and Groshong, 1998; Thomas and Bayona, 2005). Indeed, many second-order folds within the Late Paleozoic section are developed above these secondary detachments in the frontal thrust sheets, and complexly deformed carbonate duplexes are preserved in the interior of the thrust belt adjacent to the metamorphic front.

Common structures in the frontal part of the southern Appalachian thrust belt, where the Chattanooga Shale is being developed, are ramp anticlines with relatively steep forelimbs and gently dipping backlimbs (e.g., Maher, 2002; Gates, 2006; Groshong, 2005, 2006) (figs. 9, 10). GeoMet's wells in Cullman and Blount Counties are drilled in hinge zones associated with these structures. In Cullman County, the wells are located in the hinge defining the boundary between the distal forelimb of the Sequatchie anticline and the Black Warrior basin. The southeastern area, by contrast, is in the hinge between the flat-bottomed Coalburg syncline and the dipping backlimb of the Straight Mountain structure, which is a large ramp anticline associated with a major backthrust. Southern Appalachian fold hinges have been characterized as zones of enhanced natural fracturing associated with sweet spots for gas and water production in coalbed methane reservoirs (Pashin and Groshong, 1998; Pashin, 2005; Groshong et al., 2009), and similar hinge effects may influence the performance of shale reservoirs.

Bailey (2007) interpreted a seismic profile that shows the geometry of the Greene-Hale synclinorium in Greene County (fig. 11). This profile shows that thrust belt structure below the Gulf of Mexico coastal plain is dominated by a ramp-flat geometry that differs significantly from the exposed frontal structures farther northeast. A large frontal ramp defines the boundary between the Appalachian thrust belt and the Black Warrior basin, and repetition of the Cambrian-Ordovician carbonate section in the hanging wall defines an imbricate pair of thrust panels with large displacement. Devonian and younger strata of the Greene-Hale synclinorium are preserved in the hanging wall of the imbricate thrust panels and are thickest at the southeastern end of the profile. A large ramp anticline is developed within the synclinorium and has been the subject of exploration activity. The Ethel M. Koch 10-6 #1 well penetrated the crest of the anticline as well as a thrust fault that places Cambrian Conasauga limestone on top of the Cambrian-Ordovician Knox Group. The Bayne-Etheridge well was drilled in the backlimb of the anticline, and the dipmeter log confirms that dip is about 20° SE.

The Devonian shale formations considered herein are part of a weak lithotectonic unit that is bounded above and below by stiff carbonate rocks. The shale is typically fractured and sheared (fig. 2). Orthogonal

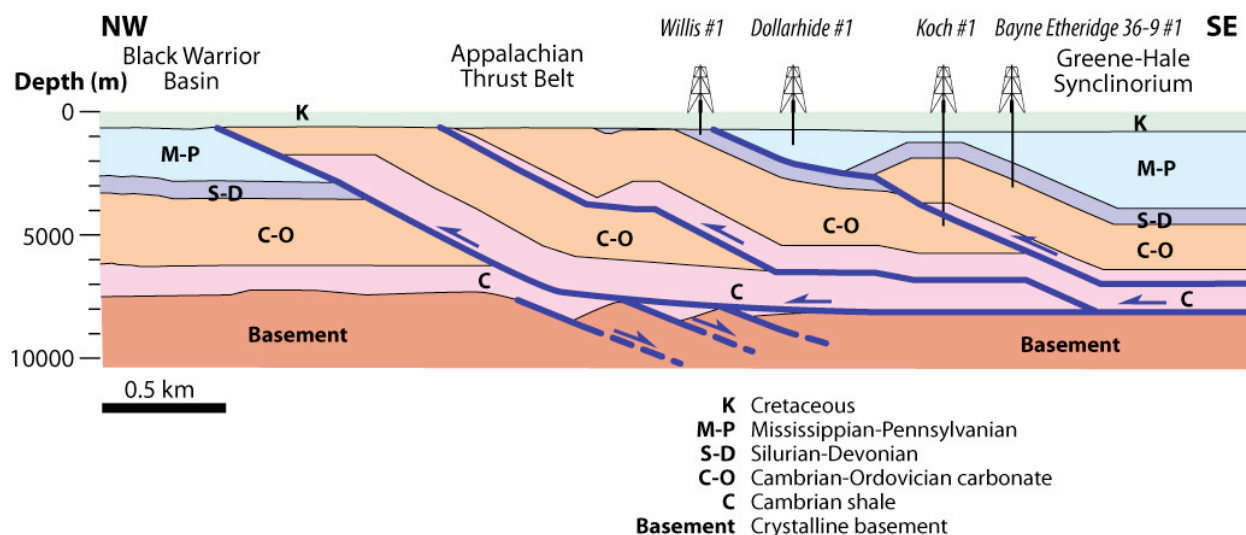


Figure 11.— Structural interpretation of the Appalachian thrust belt and the Greene-Hale synclinorium based on a regional seismic profile (modified from Bailey, 2007).

joints are abundant in the shale. Some joints extend through the full thickness of the shale, whereas others are restricted to thin beds (fig. 6B). The joints are perpendicular to bedding and typically have spacing on the order of feet. This is considerably closer than joint spacing in the adjacent carbonate strata, where spacing is on the order of tens of feet. Joints are readily observed in cores of black shale and are typically filled with calcite and subordinate amounts of pyrite, silica, and clay (fig. 6A). Systematic joints tend to be vertically and laterally persistent; they typically strike east-northeast in outcrop. Cross-joints strike at high angles to systematic joints and commonly terminate at intersections with the systematic joints. Joint systems in black shale are interpreted to predate regional folding (Pashin, 2008, 2009). Joint networks in the Appalachian region with similar orientation have been interpreted as the product of a continent-wide stress field associated with the early assembly of the Pangaeon supercontinent (Engelder and Whittaker, 2006).

In many fold limbs, the shale contains shear zones characterized by faulting and small-scale folding (fig. 2). These shear zones apparently reflect flexural slip of incompetent shale between competent carbonate units. Conjugate fractures with slickensides are abundant in many of these zones, and mineralization resembles that in the joint networks. Within the Greene-Hale synclinorium, dipmeter logs indicate complex shearing and folding in some black shale intervals, and prominent gas shows are associated with some of these zones (Pashin, 2008, 2009).

HYDRODYNAMICS AND GEOTHERMICS

The hydrodynamics and geothermics of sedimentary basins play an important role in the generation, migration, retention, and production of unconventional gas and the associated reservoir fluids. In the shallow shale reservoirs of Blount and Cullman Counties, the hydrodynamic system appears to be dominated by meteoric recharge in thrust belt structures. In the Greene-Hale synclinorium, by contrast, Paleozoic strata are sheltered from surface-driven processes by the sedimentary cover of the Gulf of Mexico coastal plain (Pashin, 2009) (fig. 12).

In Blount and Cullman Counties, a significant amount of water is co-produced with shale gas, typically about 1 bbl/Mcf (Pashin, 2009). Shale has extremely low permeability, and direct measurements of absolute permeability in Devonian shale from Alabama are on the order of 0.1 microdarcy. Therefore, the

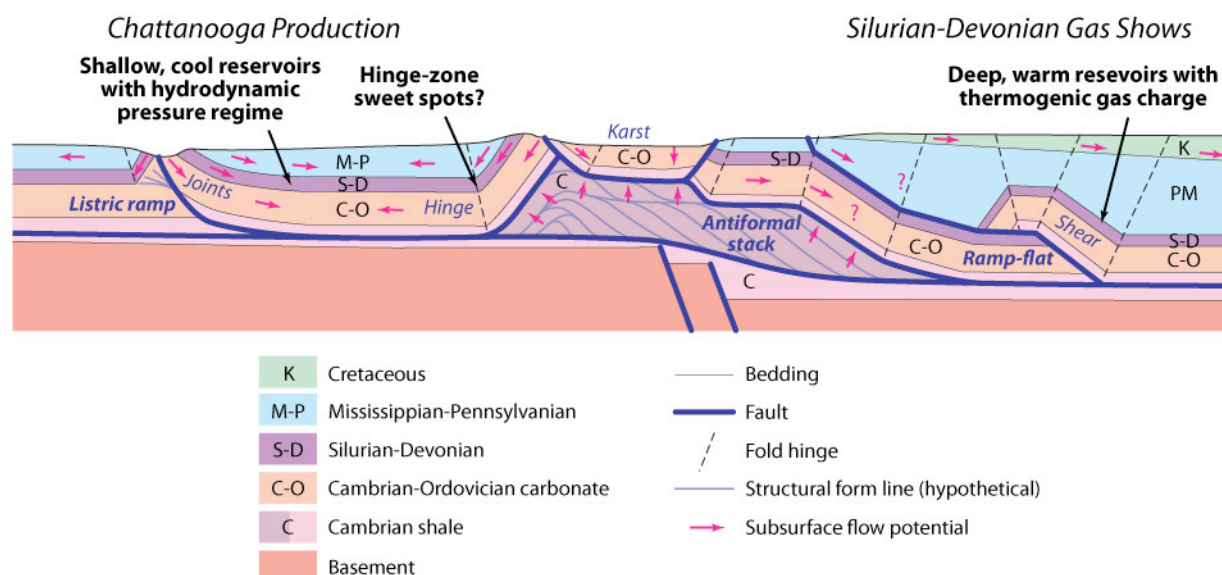


Figure 12.—Conceptual model of the hydrodynamics of Devonian shale gas reservoirs in the Appalachian thrust belt (modified from Pashin, 2009).

water is probably being produced from natural fracture systems, including joint networks and shear zones (fig. 2), and siting of the wells in fold hinges may contribute to water volume. The crestal regions of the Appalachian folds in this area are major zones of fresh-water recharge, and fresh water has been encountered in Cambrian-Ordovician carbonate rocks at depths as great as 6,000 feet. The water produced from the Chattanooga Shale, however, is more saline than that in the carbonate rocks, indicating that recharge is less effective in fractured shale than in high-permeability carbonate strata.

Farther south in the Chattanooga depocenter of the Black Warrior basin and in the Greene-Hale synclinorium, poorly consolidated Cretaceous sand and gravel accept meteoric recharge. Paleozoic carbonate rocks contain brine with elevated salinity and so meteoric recharge of these strata is ineffective below the Gulf of Mexico coastal plain (e.g., Ortiz et al., 1993). Prominent gas shows in the Devonian shale in this area have been interpreted as the product of high gas pressure in the Silurian-Devonian shale formations (Pashin, 2008; Pashin et al., 2010).

Devonian shale sits in the thermogenic gas window in much of Alabama and is in the dry gas window in the southern part of the Black Warrior basin, where vitrinite reflectance approaches 2.0 percent (Carroll et al., 1995). In the Greene-Hale synclinorium, calculated vitrinite reflectance in Devonian shale averages 2.7 percent, indicating even higher thermal maturity. These data indicate that the shale has generated significant volumes of gas, and elevated hydrocarbon pressure related to thermogenic gas charge appears to be responsible for the major gas shows in the Devonian shale. Lopatin models from the region indicate that major maturation occurred near maximum burial during the Alleghanian orogeny (Pennsylvanian-Permian) and continued during the early stages of regional unroofing during the Mesozoic (Telle et al., 1987; Carroll et al., 1995).

Modern reservoir temperatures contrast sharply between the shallow shale gas reservoirs of Blount and Cullman County and the deep reservoirs of the southeastern Black Warrior basin and the Greene-Hale synclinorium. Reservoir depth in the Blount-Cullman area is generally between 2,000 and 2,500 feet, and temperature is generally less than 89°F. Farther south, exploration is taking place in shale at depths between 7,000 and 9,000 feet, where reservoir temperature ranges from 160 to 210°F. This temperature range affects gas storage and mobility. Shale is a dual-porosity medium in which some gas is stored in open pores in a free state and some is adsorbed on organic matter. The mobility of the free gas is

governed by permeability coupled with the basic pressure-volume-temperature relationships dictated by ideal gas law. The adsorbed gas fraction, by comparison, is governed by Langmuir parameters, and adsorption isotherms flatten with increasing reservoir pressure (fig 13). Accordingly, gas mobility associated with depressurization is low at elevated reservoir pressure. In addition, the adsorption capacity of organic matter decreases substantially as reservoir temperature increases (Yang and Saunders, 1985; Gasem et al., 2009).

PETROLOGY AND GEOCHEMISTRY

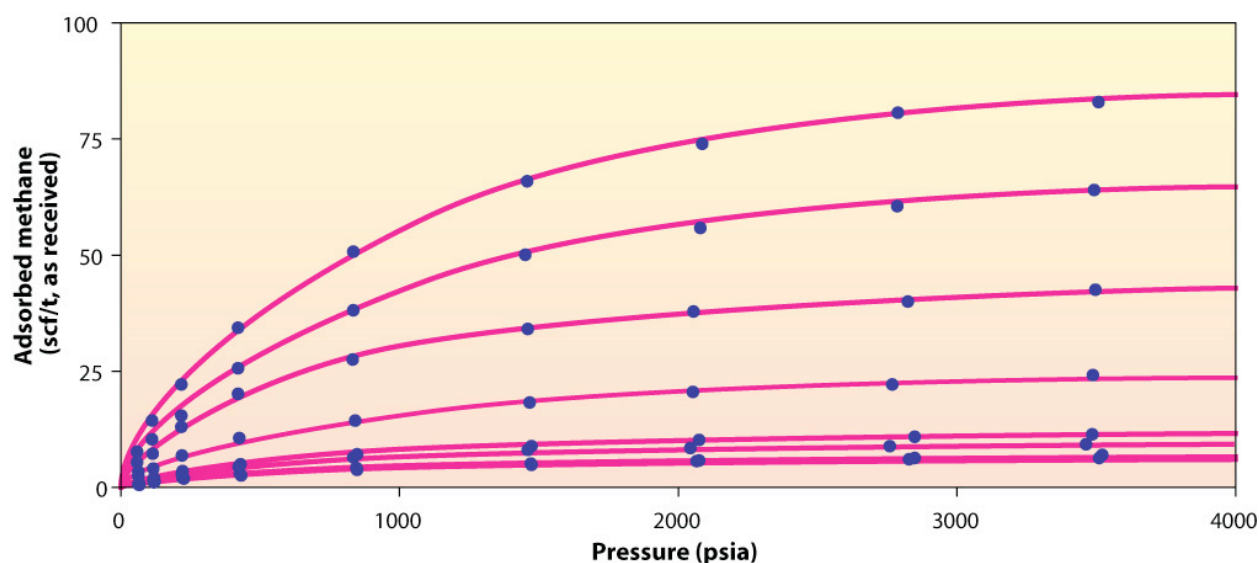
Devonian shale can appear compositionally simple to the naked eye, but it is quite complex and heterogeneous in terms of mineralogic composition, organic composition, and organic geochemistry. The shale constitutes a mixture of clay minerals, silica, carbonate, pyrite, and organic matter, and the proportions of these constituents vary greatly. Whereas some samples can be classified petrographically as clay shale, most can be classified as siltstone, and a few can even be classified as limestone.

The Chattanooga Shale contains a variety of clay minerals, and illite is the dominant form (Rheams and Neathery, 1984). Illite becomes increasingly dominant with increasing thermal maturity in the Devonian shale, and examination of samples from the Bayne-Etheridge 36-9 #1 well in the Greene-Hale synclinorium indicates that platy and lath forms are present (fig. 14). Detrital and biogenic silica is common in the shale. Detrital silica in the form of silt makes up the majority of many samples. Biogenic silica comes mainly from radiolarians (fig. 7) and spicules; they are abundant in some samples and absent in others. Calcite is the dominant carbonate mineral, and some dolomite has also been identified. Pyrite framboids are abundant in the shale, and nodules of pyrite, some of which fill burrows, are also common.

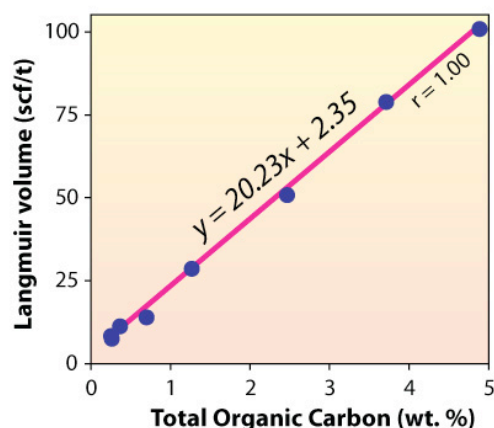
Diverse types of kerogen have been identified in the Chattanooga Shale of Alabama. Near the outcrop along the northern margin of the Black Warrior basin, where the Chattanooga contains oil shale, the shale has low thermal maturity and contains the oil-prone alga, *Tasmanites* (Rheams and Neathery, 1984). Matrix bituminite, which is amorphous kerogen that forms a fluorescent groundmass in the shale, is the most abundant type of kerogen. Other kerogen types include minor amounts of vitrinite and inertinite (Carroll et al., 1995). The total organic carbon (TOC) content of the shale is highly variable. Rheams and Neathery (1984) reported TOC content as high as 19 percent along the northern rim of the Black Warrior basin and characterized the shale as an oil-prone type I to type II source rock. But in the thermally mature shale of the Greene-Hale synclinorium, TOC content is generally lower than 5 percent (fig. 15). Indeed, kerogen in Devonian shale of the Bayne-Etheridge 36-9 #1 well has low S₂ values and low hydrogen indices. Here, the shale plots principally as a type IV source rock, indicating that the thermally mature shale has devolatilized, thus exhausting most if not all of its generative potential.

Although the most thermally mature parts of the Devonian shale in Alabama have exhausted their generative potential for hydrocarbons, the shale is capable of holding large volumes of natural gas. Indeed, the frequency of gas shows in the shale points toward high gas saturation. The ubiquity of euhedral illite laths provides evidence that the shale contains significant open pore volume. Porosimetry results from the Greene-Hale synclinorium indicate that the effective porosity of the shale is 1.2 to 2.5 percent and that about 79 percent of this pore volume is gas-filled. Isotherms indicate that the shale has significant adsorption capacity for methane, even at the elevated reservoir temperatures that exist at depth (fig. 13). Results from the Bayne-Etheridge 36-9 #1 well indicate that some shale can hold more than 80 scf/t of methane. Langmuir volume correlates directly with TOC content, indicating that nearly all adsorption capacity is in the organic matter.

A. ADSORPTION ISOTHERMS



B. LANGMUIR VOLUME AND ORGANIC CARBON



**Bayne-Etheridge 36-7 #1 well
Greene County, Alabama**

Figure 13.—Adsorption isotherms for methane and plot of Langmuir volume versus total organic carbon from core of the Bayne Etheridge 36-9 #1 well, Greene County, Alabama.

DISCUSSION AND CONCLUSIONS

Analysis of organic-rich Devonian shale in Alabama provides an example of how numerous geologic factors should be considered when evaluating shale gas reservoirs. These factors include stratigraphy and sedimentation, structural geology, basin hydrodynamics, geothermics, petrology, and geochemistry. In the Black Warrior basin, the Chattanooga Shale was deposited in a cratonic extension of the main Acadian foreland basin. An exceptionally thick, unnamed Devonian shale section was preserved in the Greene-Hale synclinorium of the Appalachian thrust belt and is interpreted as a remnant of an Acadian foreland basin. Depositional processes in both areas were complex, and physical and biogenic sedimentary structures suggest sedimentation in an euxinic basin that was episodically subjected to currents, mudflows, slumps, and slides.

The Devonian shale in Alabama is preserved in diverse structural settings. Normal faulting is common in the Black Warrior basin, whereas thrust faults and related ramp anticlines predominate in the Appalachian thrust belt. The shale contains well-developed orthogonal joint systems, and shear zones are

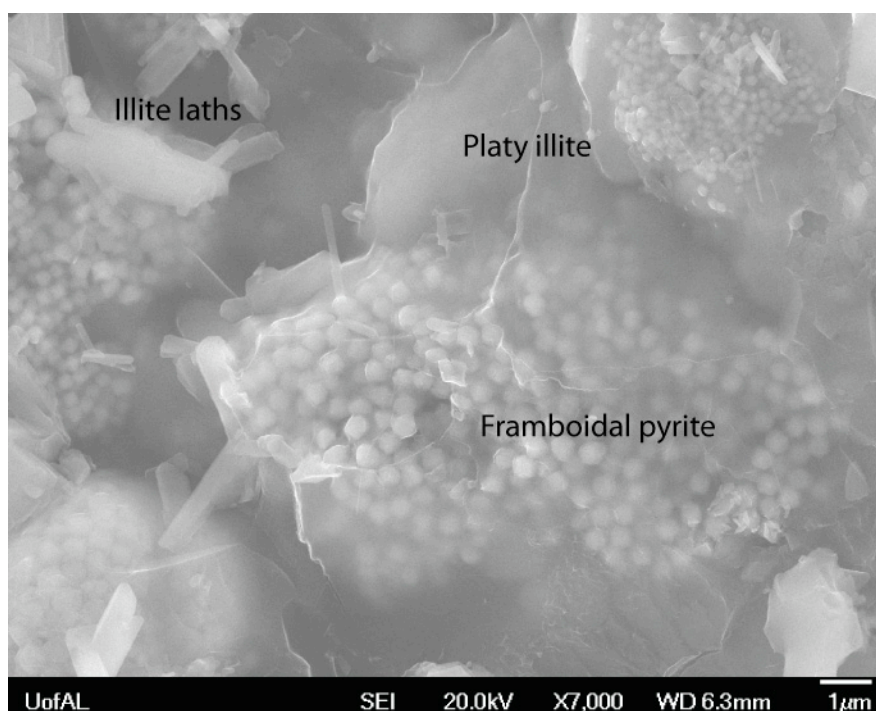


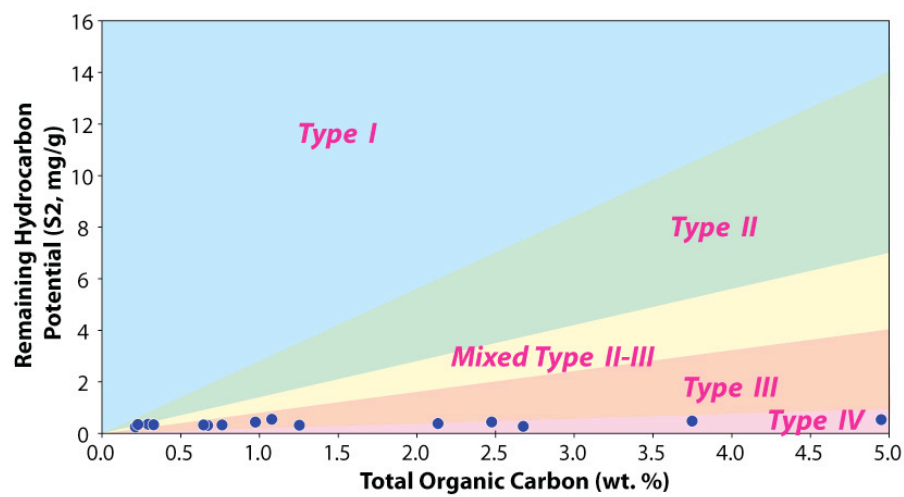
Figure 14.—Scanning electron photomicrograph of a sample from core of the Bayne Etheridge 36-9 #1 well, Greene County, Alabama showing illite forms and framboidal pyrite in Devonian black shale.

common in the thrust belt. In Blount and Cullman Counties, shale gas wells penetrate Appalachian fold hinges, which are interpreted as zones of enhanced fracturing. In the Greene-Hale synclinorium, shear zones are associated with major gas shows.

A strong hydrodynamic and geothermic contrast exists between the shallow shale reservoirs in the Appalachian frontal structures of Blount and Cullman Counties and the deep reservoirs farther south in the Black Warrior basin and the Greene-Hale synclinorium. In Blount and Cullman County, the hydrodynamic system appears to be dominated by meteoric recharge in thrust belt structures, and a significant quantity of water is co-produced with shale gas. In this area, low reservoir pressure and low reservoir temperature favor mobility of adsorbed gas. In the deep, warm reservoirs to the south, Paleozoic strata are sheltered from surface-driven processes, and major gas shows suggest that significant gas pressure remains as a product of thermogenic gas generation. In this area, high reservoir temperature and high pressure indicate that a mixture of free and adsorbed gases may be mobile.

Devonian shale contains a heterogeneous mixture of clay, silica, carbonate, pyrite and organic matter. TOC content is as high as 19 percent along the northern margin of the Black Warrior basin, where the shale is oil-prone and thermally immature with respect to gas generation. TOC values are generally lower than 5 percent where the shale is in the dry gas window, which reflects devolatilization of the parent source material. Indeed, analysis of kerogen composition indicates that the thermally mature shale has exhausted virtually all of its hydrocarbon-generative potential. However, adsorption isotherms indicate that the organic matter can store large volumes of adsorbed gas, and porosity analyses indicate that adsorbed gas is augmented significantly by free gas storage.

A. KEROGEN QUALITY



B. KEROGEN TYPE

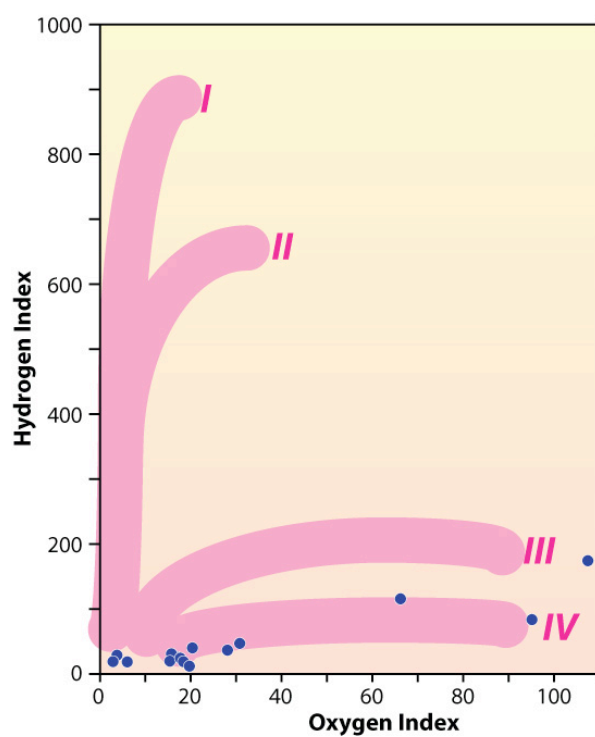


Figure 15.—Plots showing kerogen type and quality in Devonian shale from the Bayne Etheridge 36-9 #1 well, Greene County, Alabama.

ACKNOWLEDGMENT

Shale gas research at the Geological Survey of Alabama is supported by RPSEA under subcontract agreement 07122-17.

REFERENCES CITED

- Bailey, R. M., 2007, Seismic interpretation and structural restoration of a seismic profile through the southern Appalachian thrust belt under Gulf Coastal Plain sediments: Tuscaloosa, University of Alabama, unpublished Master's thesis, 71 p.
- Carroll, R. E., Pashin, J. C., and Kugler, R. L., 1995, Burial history and source-rock characteristics of Upper Devonian through Pennsylvanian strata, Black Warrior basin, Alabama: Alabama Geological Survey Circular 187, 29 p.
- Conant, L. C., and Swanson, V. E., 1961, Chattanooga Shale and related rocks of central Tennessee and nearby areas: U.S. Geological Survey Professional Paper 357, 91 p.
- Engelder, T., and Whitaker, A., 2006, Early jointing in coal and black shale: Evidence for an Appalachian-wide stress field as a prelude to the Alleghanian orogen: *Geology*, v. 34, p. 581–584.
- Ettensohn, F. R., 1985, Controls on the development of Catskill Delta complex basin-facies: Geological Society of America Special Paper 201, p. 65-77.
- Ettensohn, F. R., Miller, M. L., Dillman, S. B., Elam, T. D., Geller, K. L., Swager, D. R., Markowitz, G., Woock, R. D., and Barron, L. S., 1988, Characterization and implications of the Devonian-Mississippian black shale sequence, eastern and central Kentucky, U. S. A.: pycnoclines, transgression, regression, and tectonism, in McMillan, N. J., Embry, A. F., and Glass, D. J., eds., *Devonian of the World, Proceedings of the Second International Symposium on the Devonian System*: Canadian Society of Petroleum Geologists Memoir 14, v. 2, p. 323-345.
- Farrell, S. G., and Eaton, S., 1987, Slump strain in the Tertiary of Cyprus and the Spanish Pyrenees: definition of palaeoslopes and soft-sediment deformation, in M. E. Jones and R. M. F. Preston, eds., *Deformation of Sediments and Sedimentary Rocks*: London Geological Society Special Publication 29, p. 181-196.
- Gasem, K. A. M., Pan, Z., Mohammad, S., and Robinson, R. L., Jr., 2009, Two-dimensional equation of state modeling of adsorbed coalbed methane gases: *American Association of Petroleum Geologists Studies in Geology* 59, p. 475-497.
- Gates, M. G., 2006, Structure of the Wills Valley anticline in the vicinity of Mentone, Alabama: Tuscaloosa, University of Alabama, unpublished Master's thesis, 46 p.
- Groshong, R. H., Jr., 2005, Listric-thrust kinematic model for thin-skinned, highly asymmetric, Wills Valley anticline, southern Appalachians: *Geological Society of America Abstracts with Programs*, v. 37, no. 7, p. 234.
- Groshong, R. H., Jr., 2006, 3-D structural geology—A practical guide to quantitative surface and subsurface map interpretation: New York, Springer, 400 p.
- Groshong, R. H., Jr., Hawkins, W. B., Jr., Pashin, J. C., and Harry, D. L., 2010, Extensional structures of the Alabama promontory and Black Warrior foreland basin: Styles and relationship to the Appalachian

- fold-thrust belt, in Bartholomew, M. J., ed., *From Rodinia to Pangea: The lithotectonic record of the Appalachian region: Geological Society of America Special Paper*, in press.
- Groshong, R. H., Jr., Pashin, J. C., McIntyre, M. R., 2009, Structural controls on fractured coal reservoirs in the southern Appalachian Black Warrior foreland basin: *Journal of Structural Geology*, v. 31, p. 874-886, doi:10.1016/j.jsg.2008.02.017.
- Kidd, J. T., 1975, Pre-Mississippian stratigraphy of the Warrior Basin: *Gulf Coast Association of Geological Societies Transactions*, v. 25, p. 20-39.
- Maher, C. A., 2002, Structural deformation of the southern Appalachians in the vicinity of the Wills Valley anticline, northeast Alabama: Tuscaloosa, University of Alabama, unpublished Master's thesis, 45 p.
- Ortiz, I., Weller, T. F., Anthony, R. V., Frank, J., Linz, D., and Nakles, D., 1993, Disposal of produced waters: Underground injection option in the Black Warrior Basin, 1993 International Coalbed Methane Symposium Proceedings, p. 339-364.
- Pashin, J. C., 1994, Flexurally influenced eustatic cycles in the Pottsville Formation (Lower Pennsylvanian), Black Warrior basin, Alabama, in Dennison, J. M., and Ettensohn, F. R. eds., *Tectonic and Eustatic Controls on Sedimentary Cycles: Society of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology*, v. 4, p. 89-105.
- Pashin, J. C., 2004, Cyclothems of the Black Warrior basin in Alabama: eustatic snapshots of foreland basin tectonism, in Pashin, J. C. and Gastaldo, R. A., eds., *Sequence stratigraphy, paleoclimate, and tectonics of coal-bearing strata: American Association of Petroleum Geologists Studies in Geology* 51, p. 199-217.
- Pashin, J. C., 2005, Coalbed methane exploration in thrust belts: experience from the southern Appalachians, USA: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 2005 International Coalbed Methane Symposium Proceedings, paper 0519, 14 p.
- Pashin, J. C., 2008, Gas shale potential of Alabama: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 2008 International Coalbed & Shale Gas Symposium Proceedings, paper 0808, 13 p.
- Pashin, J. C., 2009, Shale gas plays of the southern Appalachian thrust belt: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 2009 International Coalbed & Shale Gas Symposium Proceedings, paper 0907, 14 p.
- Pashin, J. C., Carroll, R. E., McIntyre, M. R., and Grace, R. L. B., 2010, Geology of unconventional gas plays in the southern Appalachian thrust belt: *Society for Sedimentary Geology (SEPM) Guidebook, Field Trip 7*, American Association of Petroleum Geologists Annual Conference and Exposition, New Orleans, Louisiana.
- Pashin, J. C., and Ettensohn, F. R., 1992, Paleogeology and sedimentology of the dysaerobic Bedford fauna (Late Devonian), Ohio and Kentucky (USA): *Palaeogeography, Palaeoclimatology, and Palaeoecology*, v. 91, p. 21-34.
- Pashin, J. C., and Ettensohn, F. R., 1995, Reevaluation of the Bedford-Berea sequence in Ohio and adjacent states: forced regression in a foreland basin: *Geological Society of America Special Paper* 298, 68 p.

- Pashin, J. C., and Groshong, R. H., Jr., 1998, Structural control of coalbed methane production in Alabama: *International Journal of Coal Geology*, v. 38, p. 89-113.
- Pashin, J. C., and Rindsberg, A. K., 1993, Origin of the carbonate-siliciclastic Lewis cycle (Upper Mississippian) in the Black Warrior basin of Alabama: *Alabama Geological Survey Bulletin* 157, 54 p.
- Rheams, K. F., and Neathery, T. L., 1988, Characterization and geochemistry of Devonian oil shale, north Alabama, northwest Georgia, and south-central Tennessee (a resource evaluation): *Alabama Geological Survey Bulletin* 128, 214 p.
- Rodgers, John, 1950, Mechanics of Appalachian folding as illustrated by the Sequatchie anticline, Tennessee and Alabama: *American Association of Petroleum Geologists Bulletin*, v. 34, p. 672-681.
- Schieber, J., 1994, Evidence for episodic high energy events and shallow water deposition in the Chattanooga Shale, Devonian, central Tennessee, U.S.A.: *Sedimentary Geology*, v. 93, p. 193-208.
- Telle, W. R., Thompson, D. A., Lottman, L. K., and Malone, P. G., 1987, Preliminary burial-thermal history investigations of the Black Warrior basin: implications for coalbed methane and conventional hydrocarbon development: Tuscaloosa, Alabama, University of Alabama, 1987 Coalbed Methane Symposium Proceedings, p. 37-50.
- Thomas, W. A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: *American Journal of Science*, v. 277, p. 1233-1278.
- Thomas, W. A., 1985, Northern Alabama sections, in Woodward, N. B., ed., *Valley and Ridge thrust belt: balanced structural sections, Pennsylvania to Alabama*: University of Tennessee Department of Geological Sciences Studies in Geology 12, p. 54-60.
- Thomas, W. A., 1988, The Black Warrior basin, in Sloss, L. L., ed., *Sedimentary cover—North American craton*: Geological Society of America, *The Geology of North America*, v. D-2, p. 471-492.
- Thomas, W. A., 2001, Mushwad: Ductile duplex in the Appalachian thrust belt in Alabama: *American Association of Petroleum Geologists Bulletin*, v. 85, p. 1847-1869.
- Thomas, W. A., and Bayona, G., 2005, The Appalachian thrust belt in Alabama and Georgia: thrust-belt structure, basement structure, and palinspastic reconstruction: *Alabama Geological Survey Monograph* 16, 48 p.
- Yang, R.T., and J.T. Saunders, 1985, Adsorption of gases on coals and heat-treated coals at elevated temperature and pressure: *Fuel*, v. 64, p. 616-620.